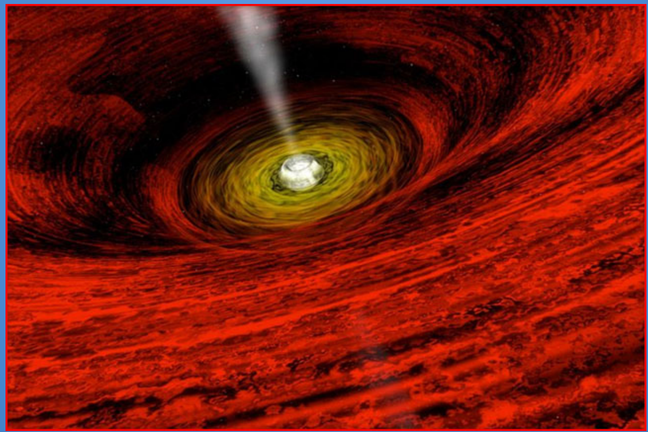
Black Hole Universe

UNIVERSITY OF Southampton
School of Physics and Astronomy

Fast timing tests of strong gravity

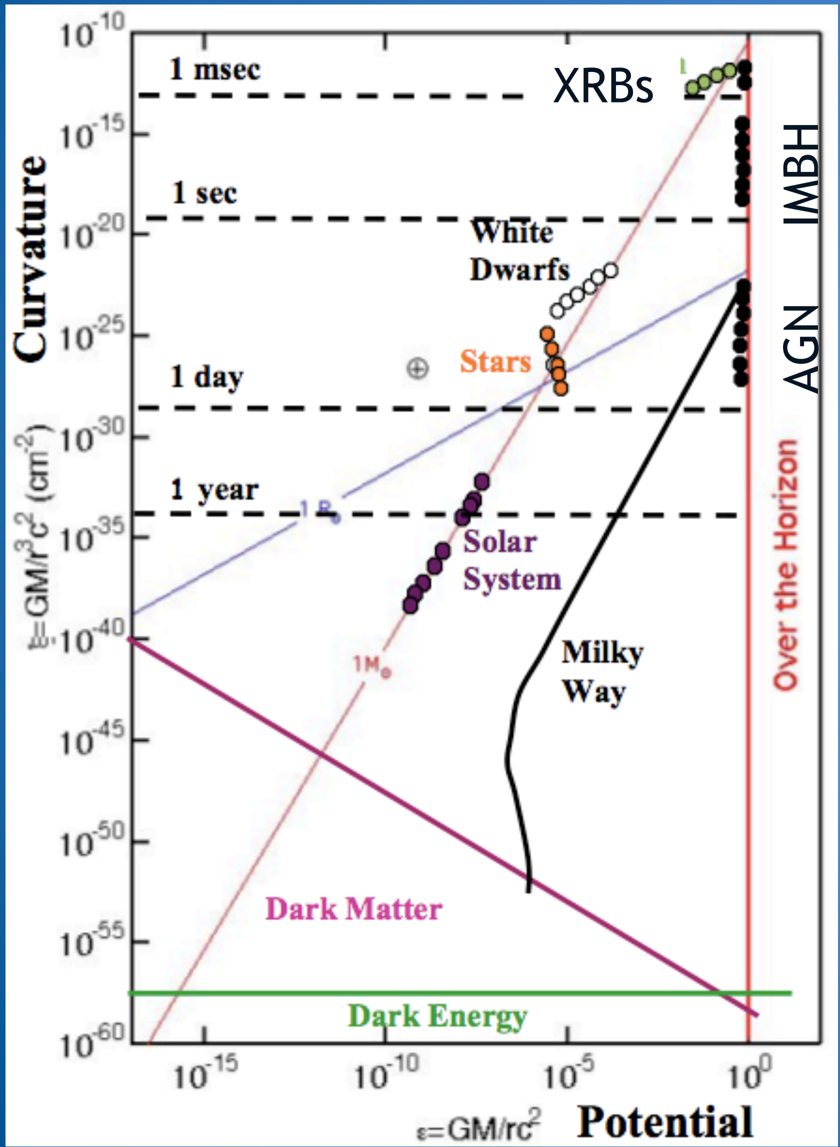


Phil Uttley

Getting close to black holes: the innermost 100 R_G

- Responsible for up to ~98% of accretion power output.
- Launch-site of the most powerful outflows and jets.
- Strongest gravitational potential in the universe.
- In stellar mass BH, the greatest spacetime curvatures that we know to exist.

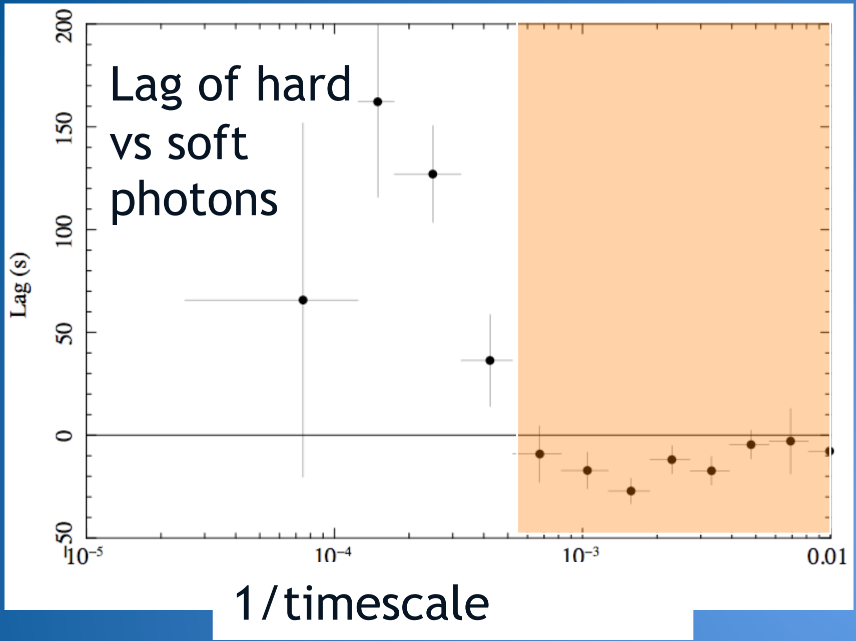
The strong gravity regime

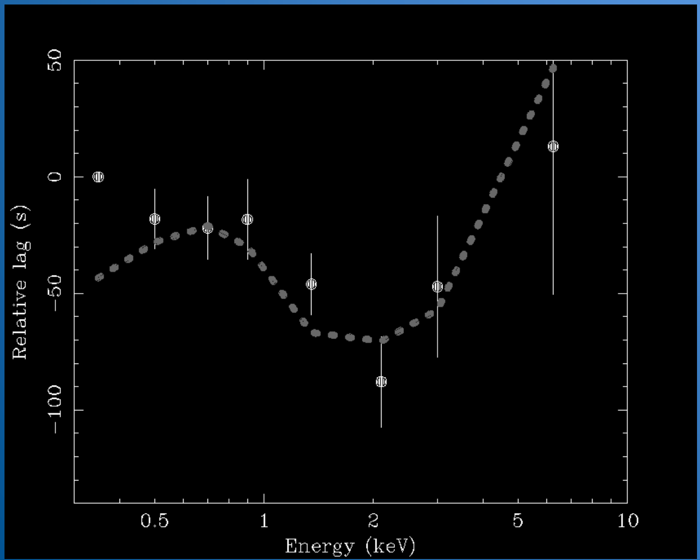


The most extreme space-time is found around stellar-mass BH & NS, and corresponds to smallest light-crossing time-scales, and the fastest variability signals.

(Psaltis 2008)

Mapping the inner accretion flow





- Time delays are observed between variations at different energies.
- For the first time, the fastest of these can be identified with reverberation of the continuum off the disc (e.g. in AGN 1H0707-495, Fabian et al. 2009, Zoghbi et al. 2010

Why IXO?

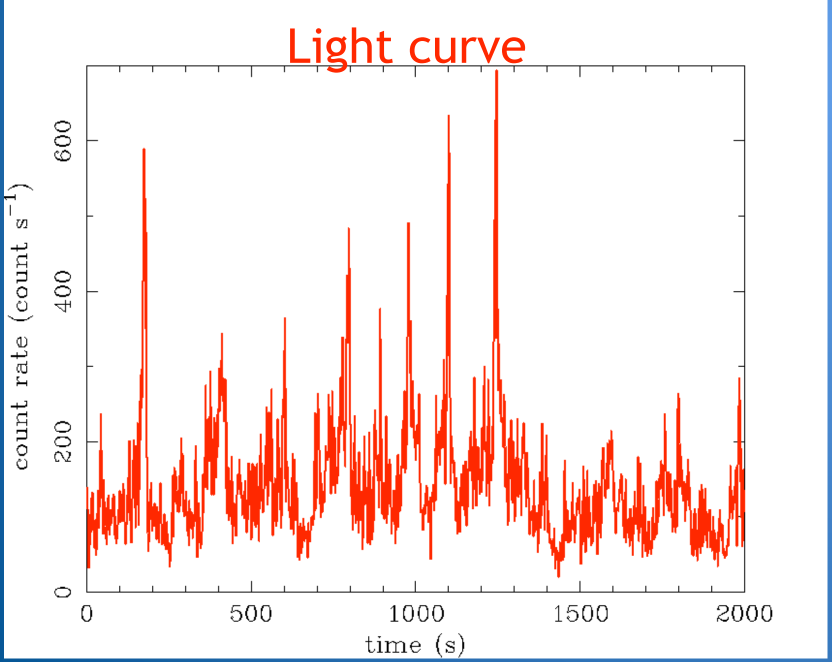
- Fastest variations probe smallest regions (simple light-travel/causality arguments)
- Need high S/N to probe fastest variations
- Two S/N regimes:
  - **many photons/variability-cycle**: S/N scales as sqrt(rate)
  - **few photons/variability-cycle**: S/N scales linearly with rate
- AGN are in former regime, XRBs in latter, hence we see biggest improvements for XRBs at the highest count rates: optimal for HTRS observations of XRBs

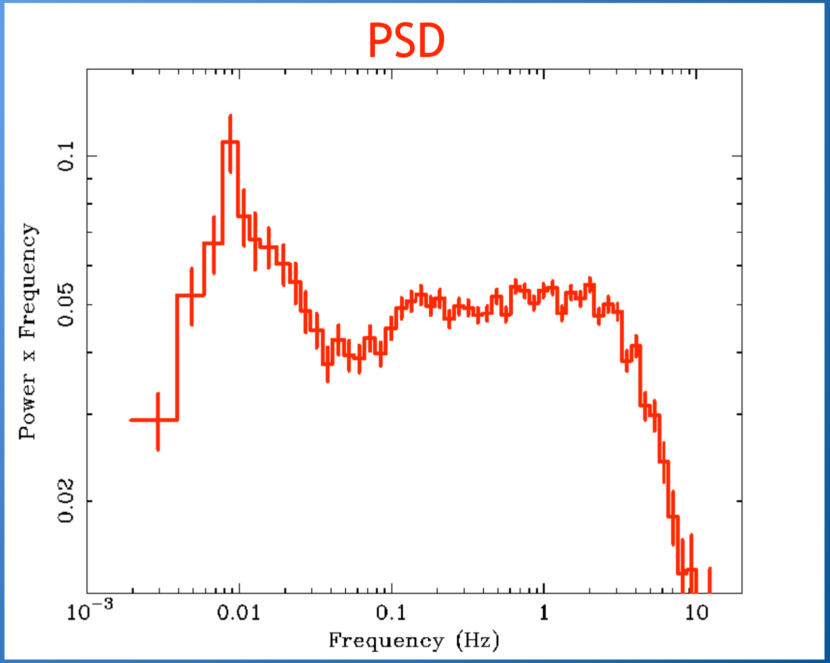
Probing the fastest signals around black holes

Basic X-ray timing

Light curves show variations on a broad range of time-scales. The Power Spectral Density shows the rms-squared amplitude of variation as a function of Fourier frequency (1/timescale)

GX 339-4 2009 hard state 0.5-10 keV (XMM-Newton EPIC-pn)



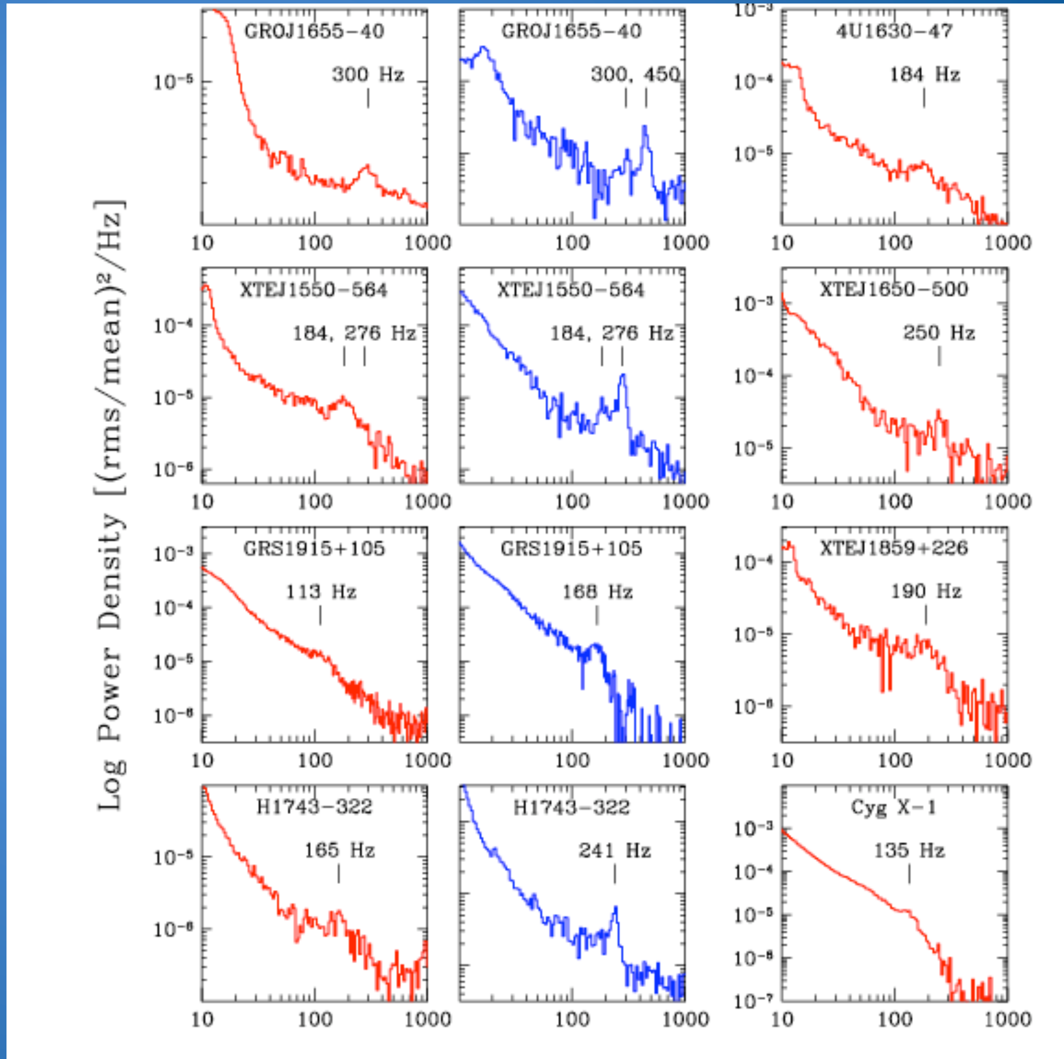


High-frequencies: what do we see now?

✧ Detection of high-frequency QPOs is a major legacy of RXTE

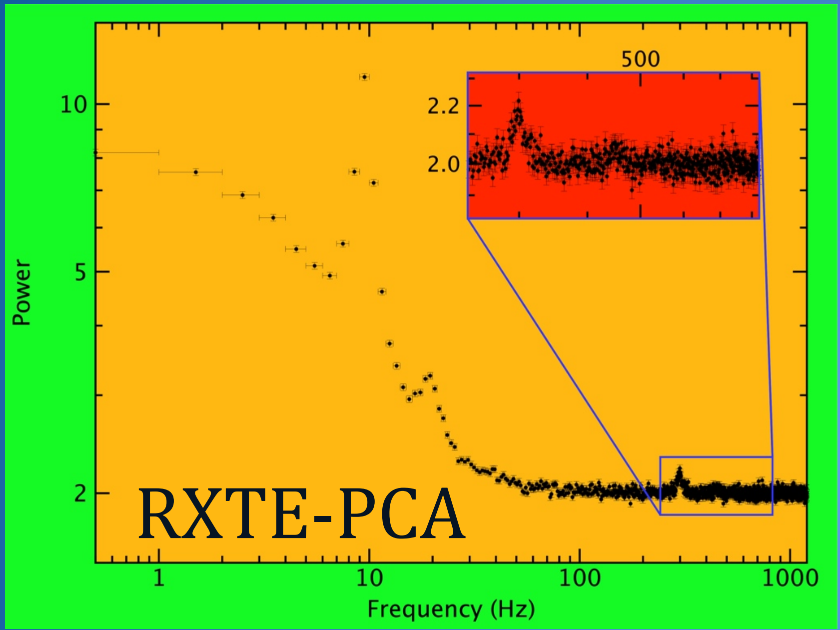
✧ Interpretations centre around one or more General relativistic epicyclic resonant frequencies at inner disc edge

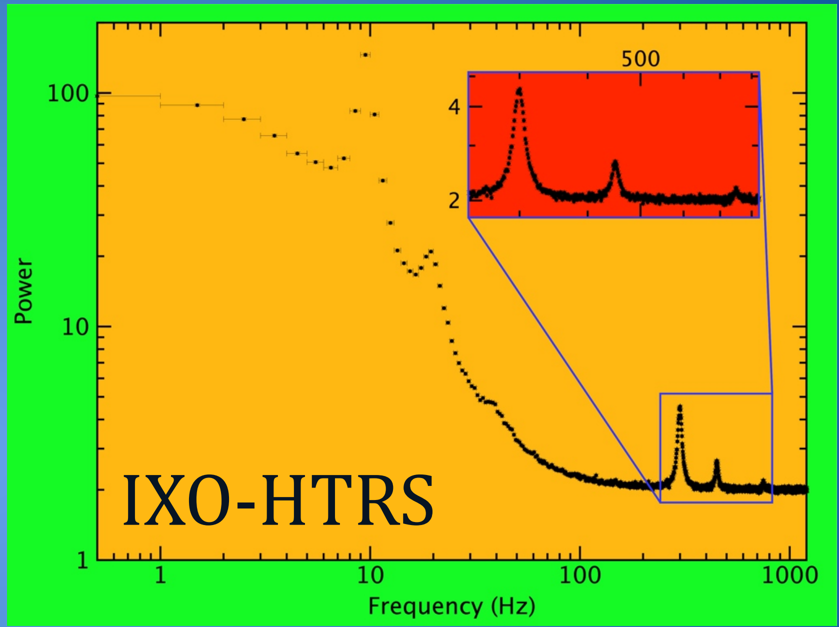
✧ But too few examples to pin down models



(Remillard 2010)

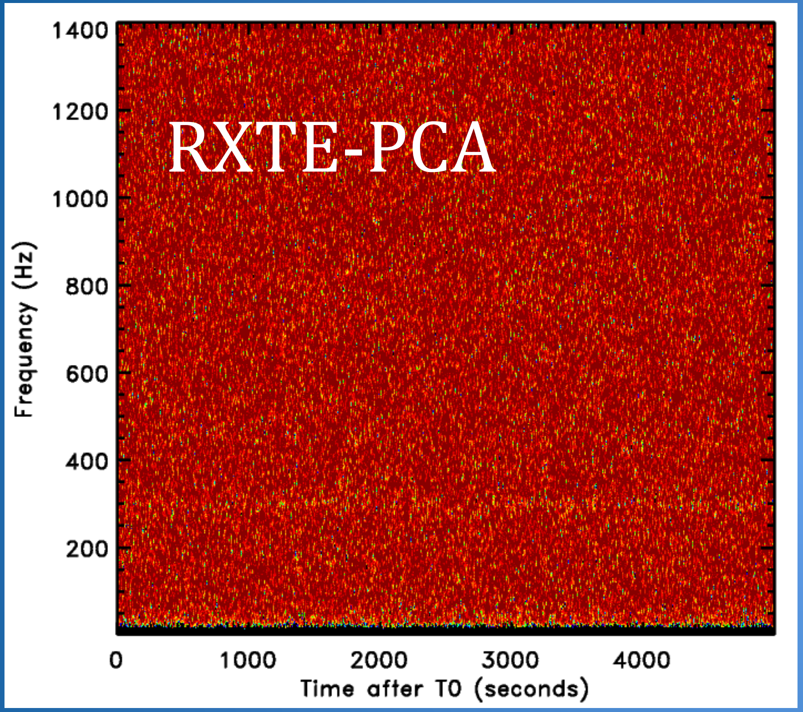
What could IXO-HTRS see?

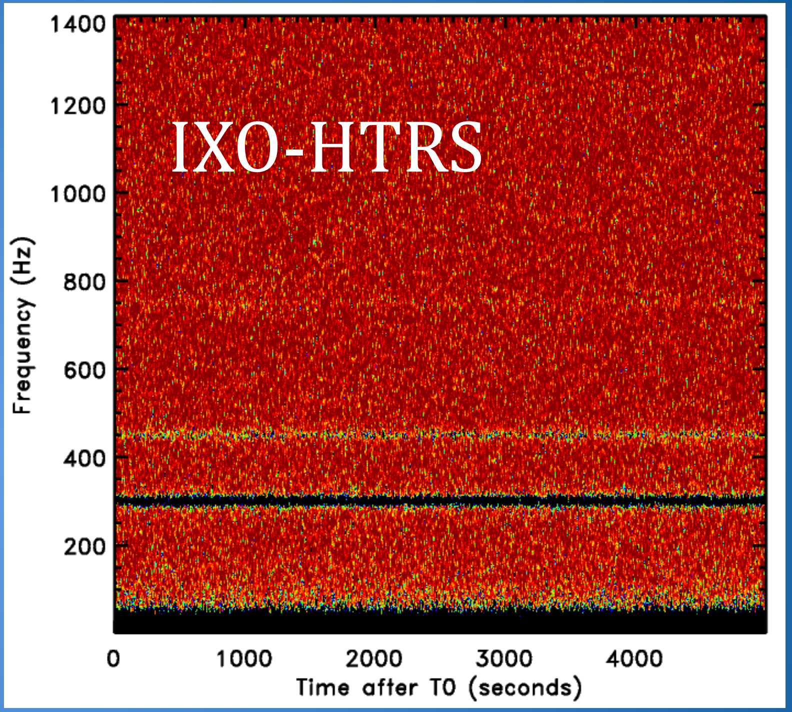




- Even allowing for hard spectral shape of QPOs, IXO-HTRS combination allows detection of signals down to <0.25% rms
- Soft X-ray response also opens up new discovery space of QPOs associated with the accretion disc

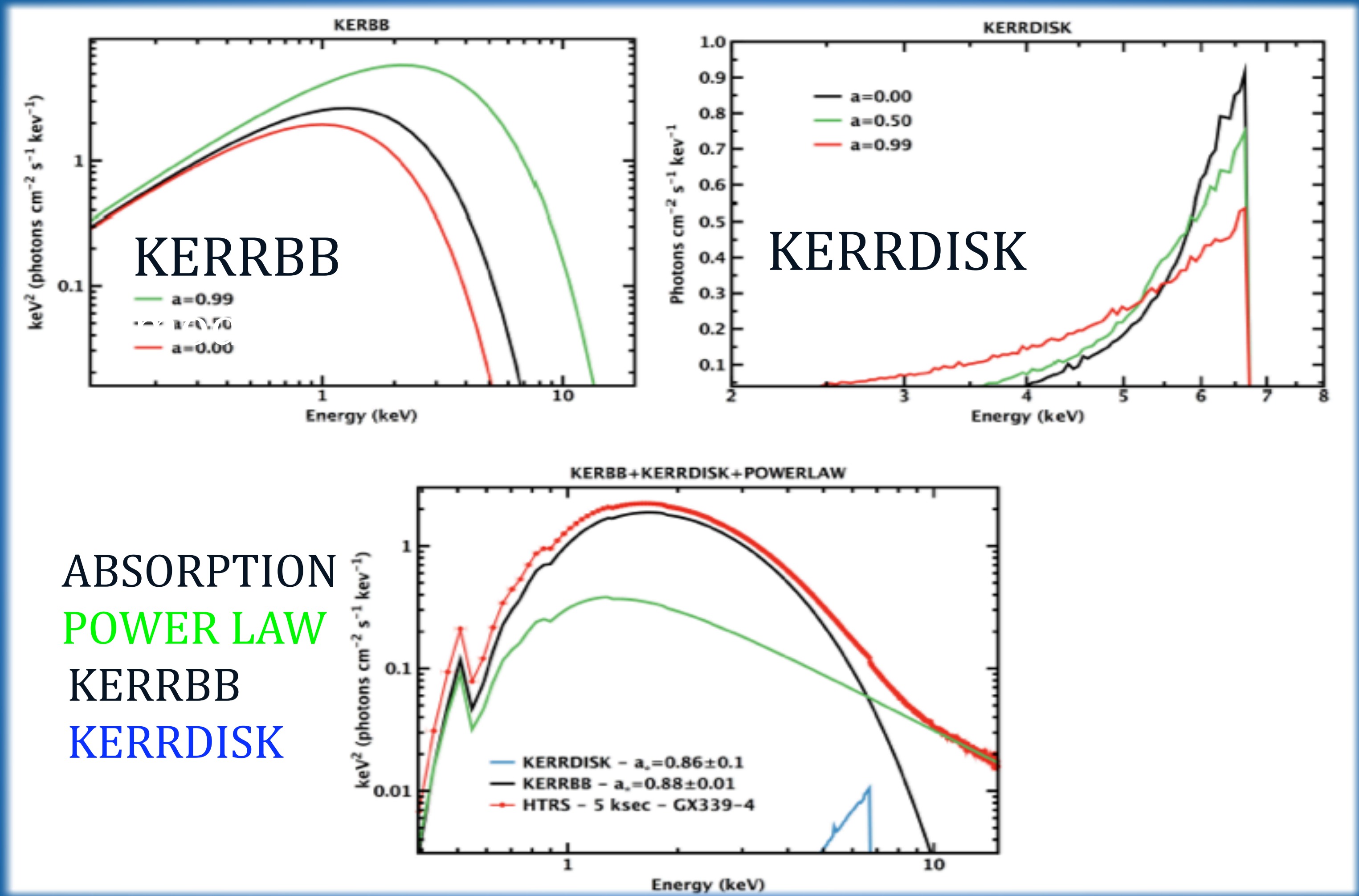
Tracking the QPO on 1s time-scales





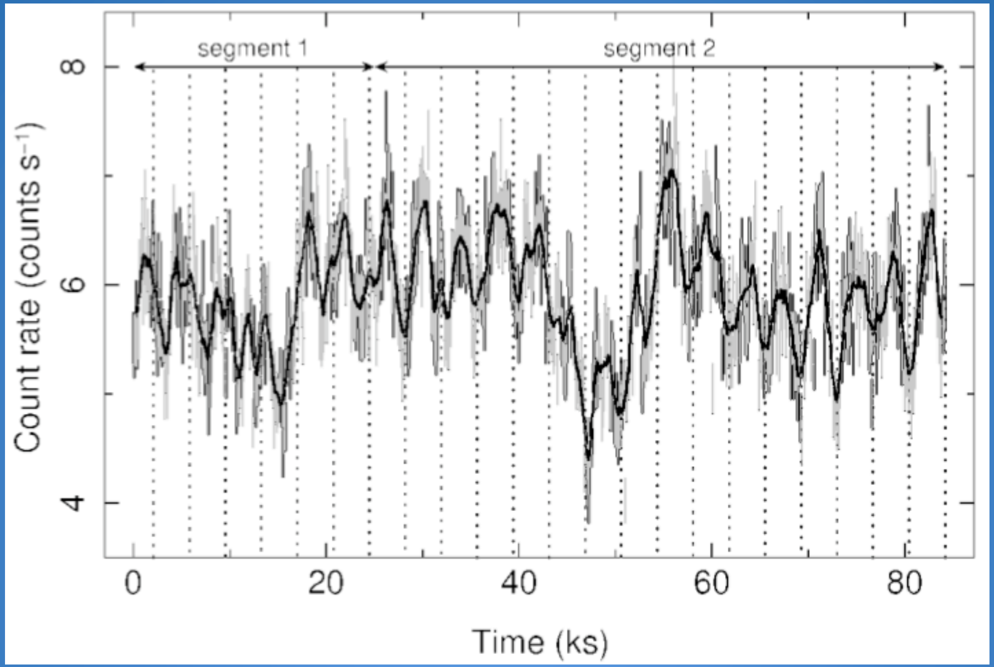
Stability of frequency would prove epicyclic GR interpretation: opens door to use of QPO to measure spin for BH with known mass

QPO+simultaneous spectral modelling



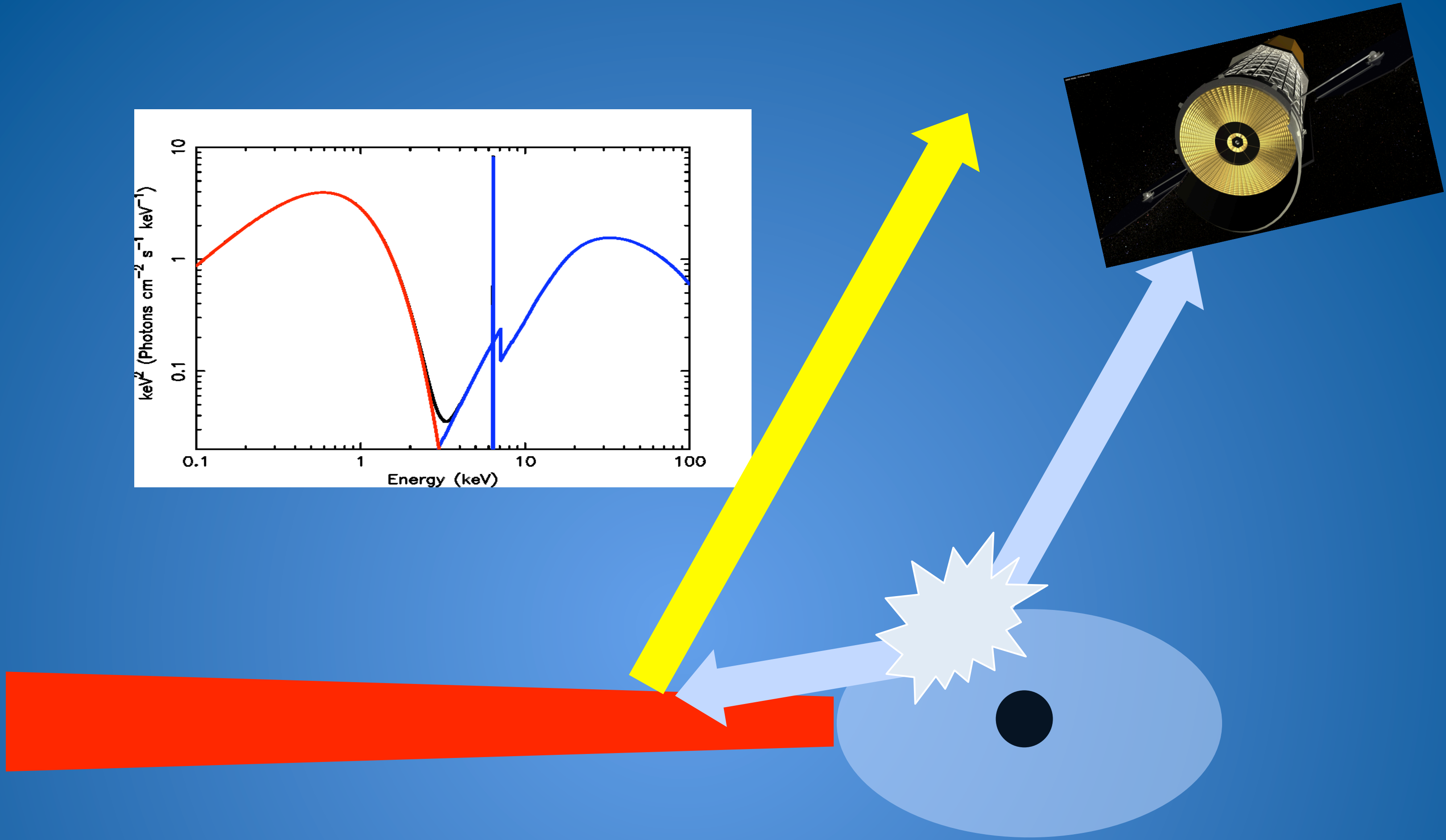
BHXRBs will allow simultaneous comparison of several independent techniques to estimate spin

What about HFQPOs in AGN?



- To date, only one statistically strong example (RE J1034+396, Gierlinski et al. 2008)
- However, IXO only modestly improves chances of detection, because in AGN, noise is dominated by the intrinsic variability, not Poisson effects

X-ray reverberation mapping of accreting black holes



✧ Power-law continuum varies first, followed by reflection thermally-reprocessed emission

✧ Path-length difference defines *intrinsic lag*. Observed lag is the intrinsic lag diluted by the ratio of continuum to reverberating emission

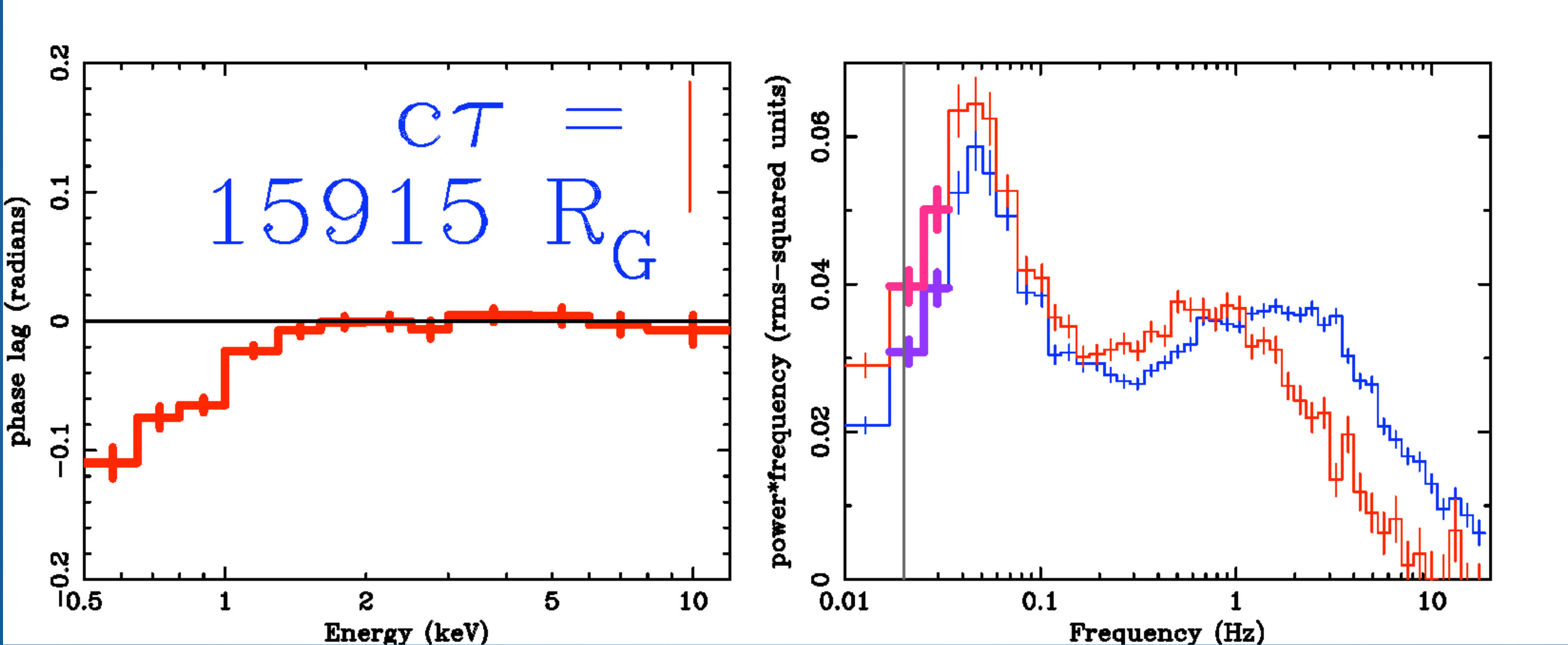
Spectral-timing methods

Use the ‘cross-power-spectrum’ (or ‘cross-spectrum’) to combine spectral and timing information and measure

lags vs energy (lag-energy): plot the lag of variations in each energy bin relative to some broad ‘reference’ energy band. Should roughly follow shape of reverberation-spectrum/continuum

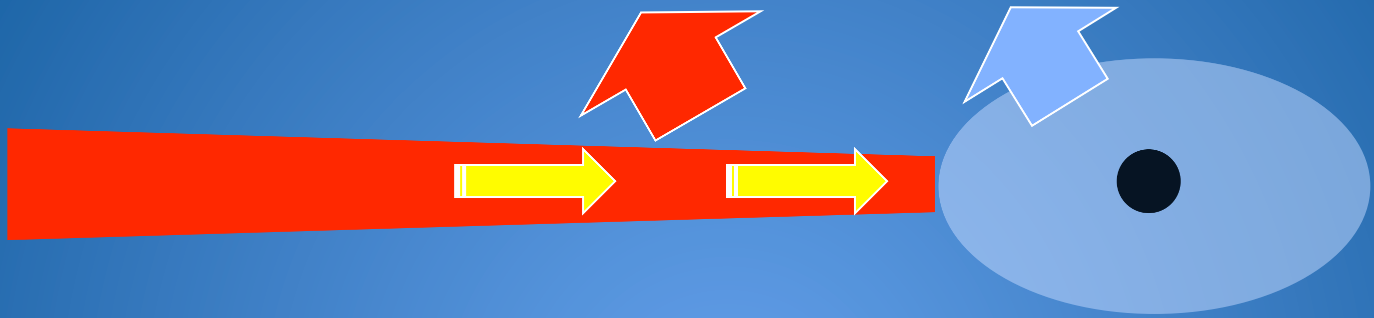
We can also define specific frequency/time-scale ranges to measure the lags over

First evidence of disk reverberation in a BHXRB

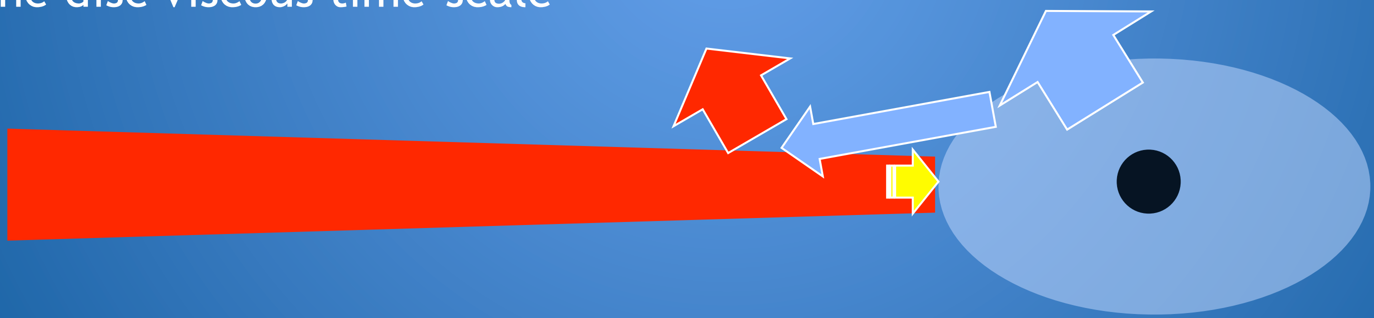


The lag behaviour is also strongly frequency-dependent, with a sign-reversal corresponding to drop in variable disc emission

Interpretation



At **low frequencies**, variations in mdot are produced at larger radius in disc, modulating disc emission before propagating in to the corona on the disc viscous time-scale



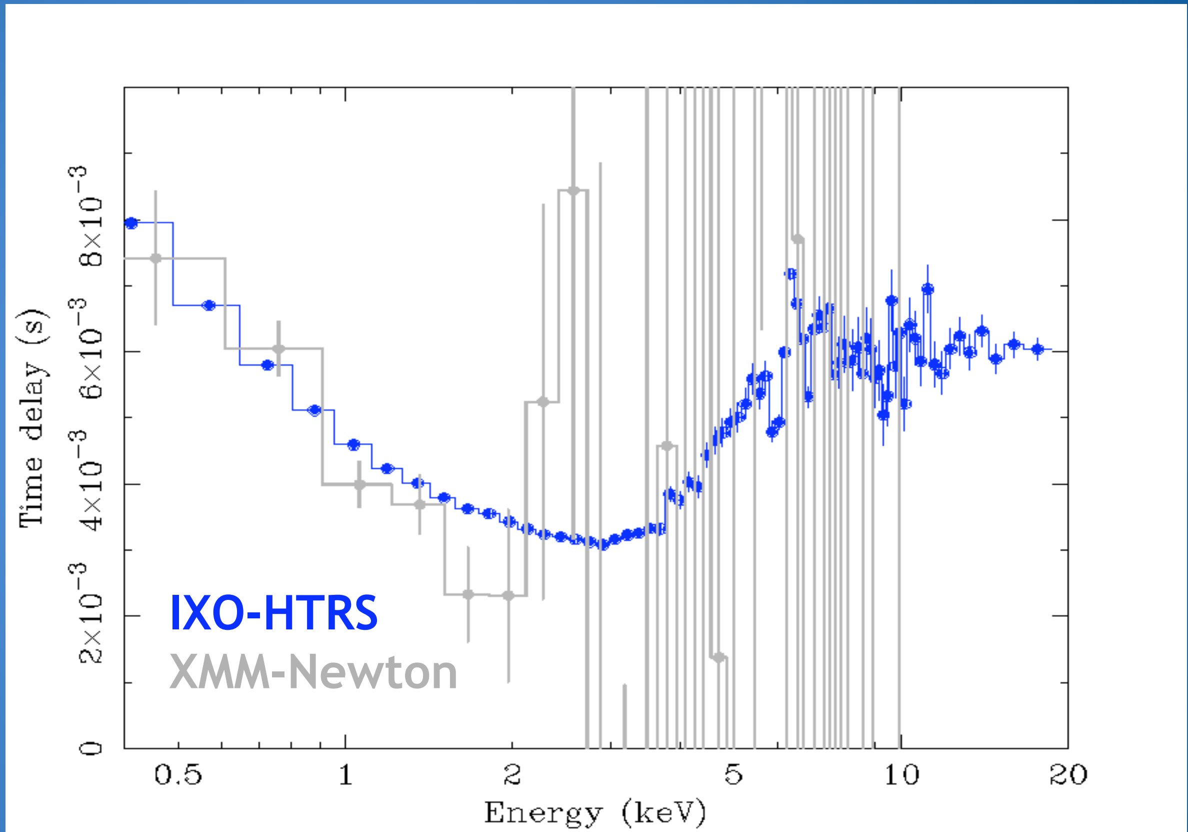
At **high frequencies**, variations in mdot are produced at small radius in disc or in corona itself. Only a fraction of disc emission can respond, but all of corona does, and coronal heating dominates variability ➔ disc reverberation

Importance of soft response

Note that the disc signature in the lags appears below 2 keV in the hard state: underlines need for a soft response to probe disk variability and thermal component of reverberation. This could never be seen with RXTE and had to wait for XMM-Newton!

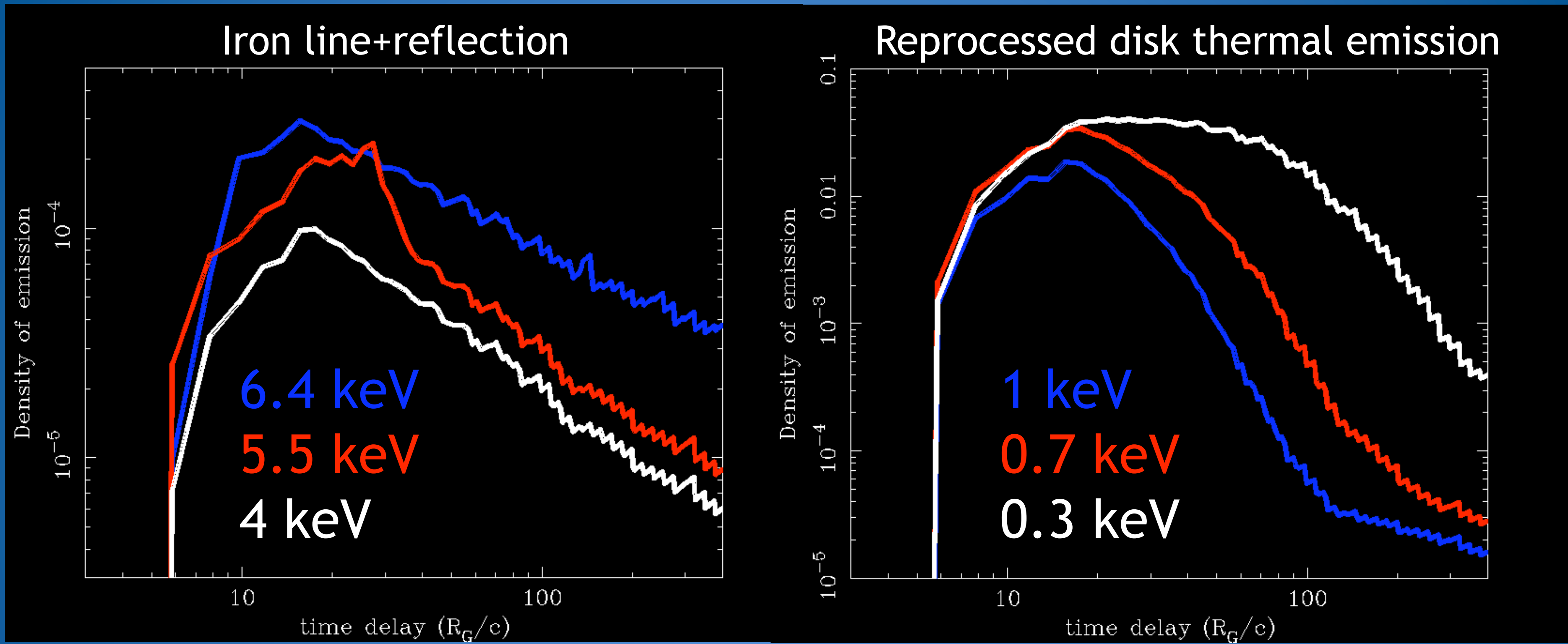
The future with IXO

Lag vs energy for 100 ksec observation of BHXRB hard state



Huge improvement since S/N scales *linearly* with count rate

How lag-vs-energy spectra map the disk



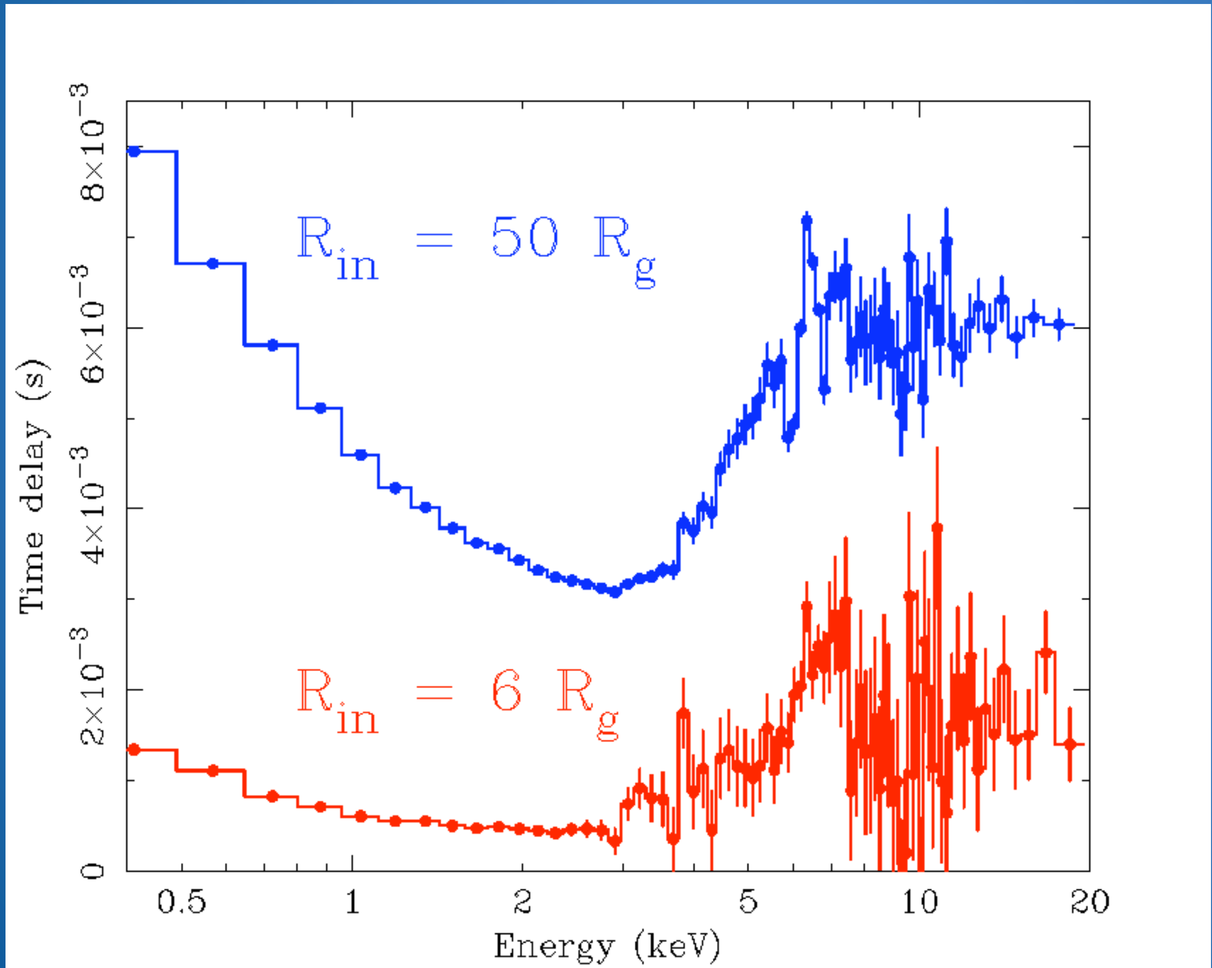
- Lag depends on emissivity vs light-travel delay (size-scale). Selecting on Fourier-frequency can pick out different parts of the emissivity profile at that energy.
- We can map the reflection and disc thermal emission

Key point: the power of measuring reverberation lags is that they give you measurements in km, not R/M (given by spectral fits).

Can use in combination with R/M measures to:

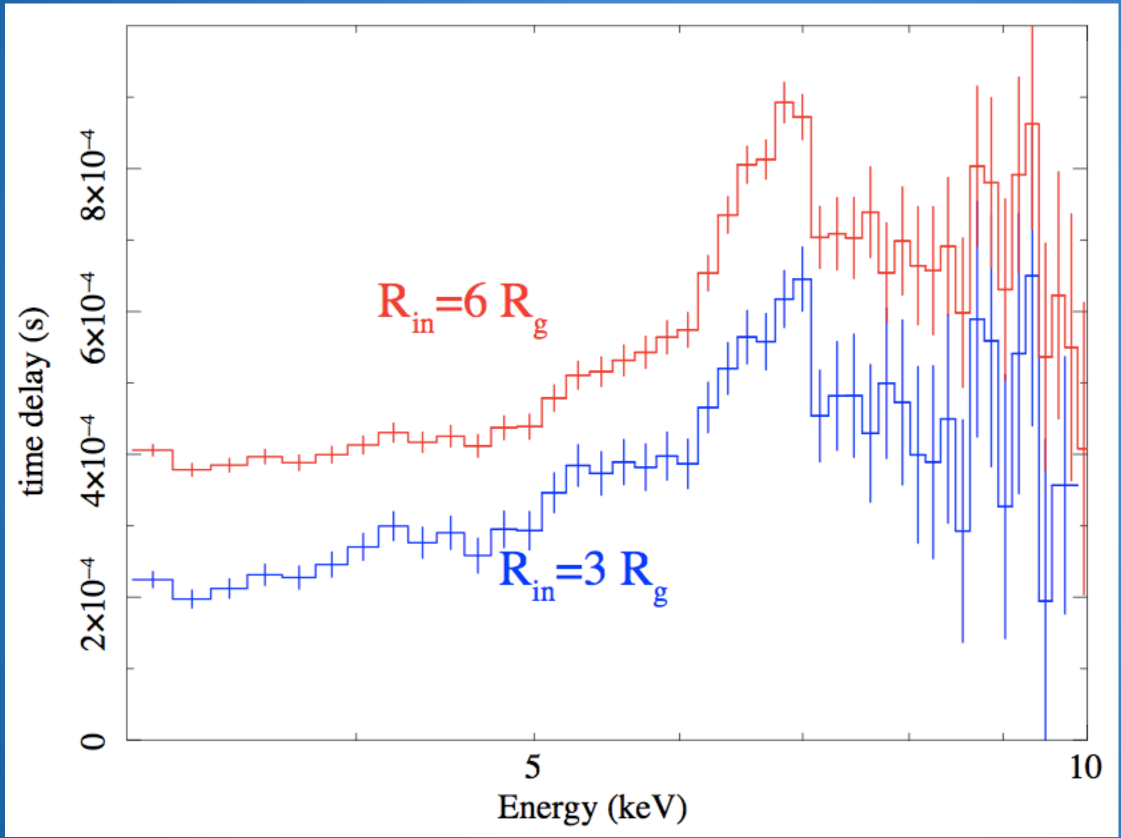
- ✧ estimate BH mass
- ✧ or with an independent estimate of mass, **carry out direct test of GR in strong-field regime**

Using IXO-HTRS to measure the disk inner radius of Cyg X-1 in the hard state



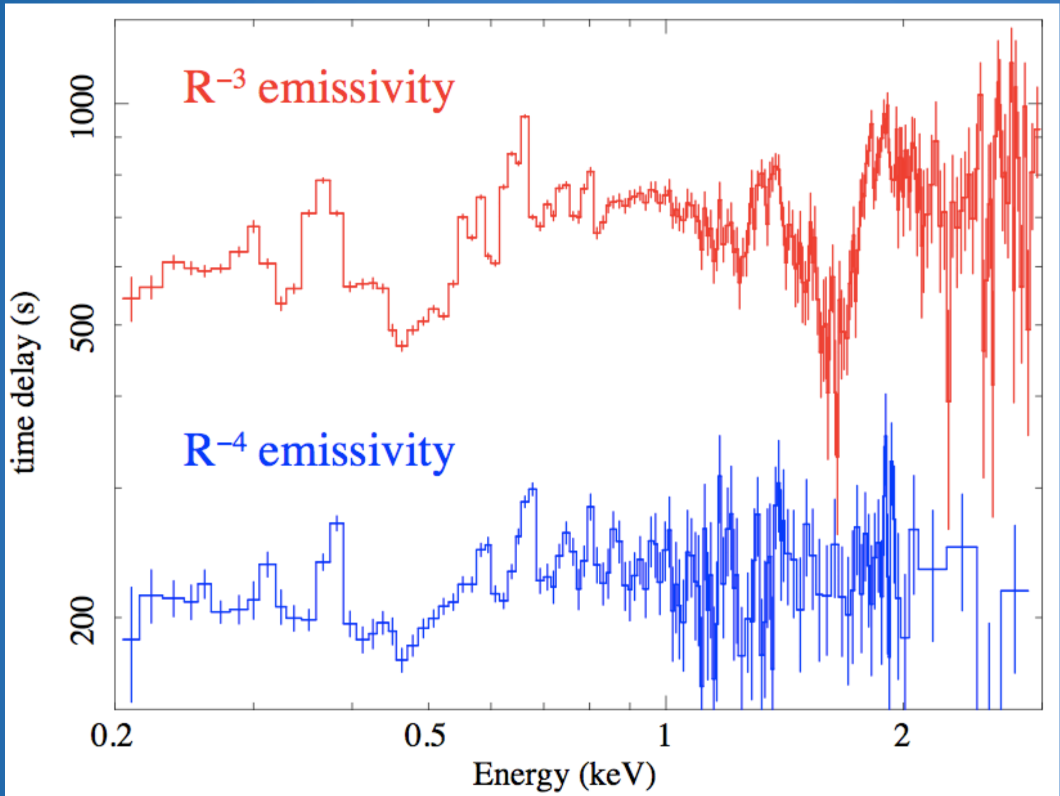
(100 ksec exposure, select variations from 50-100 Hz)

Using IXO-HTRS to map reflection from HF QPOs



(100 ksec exposure, select variations at QPO frequency)

Mapping AGN: best case NLS1s



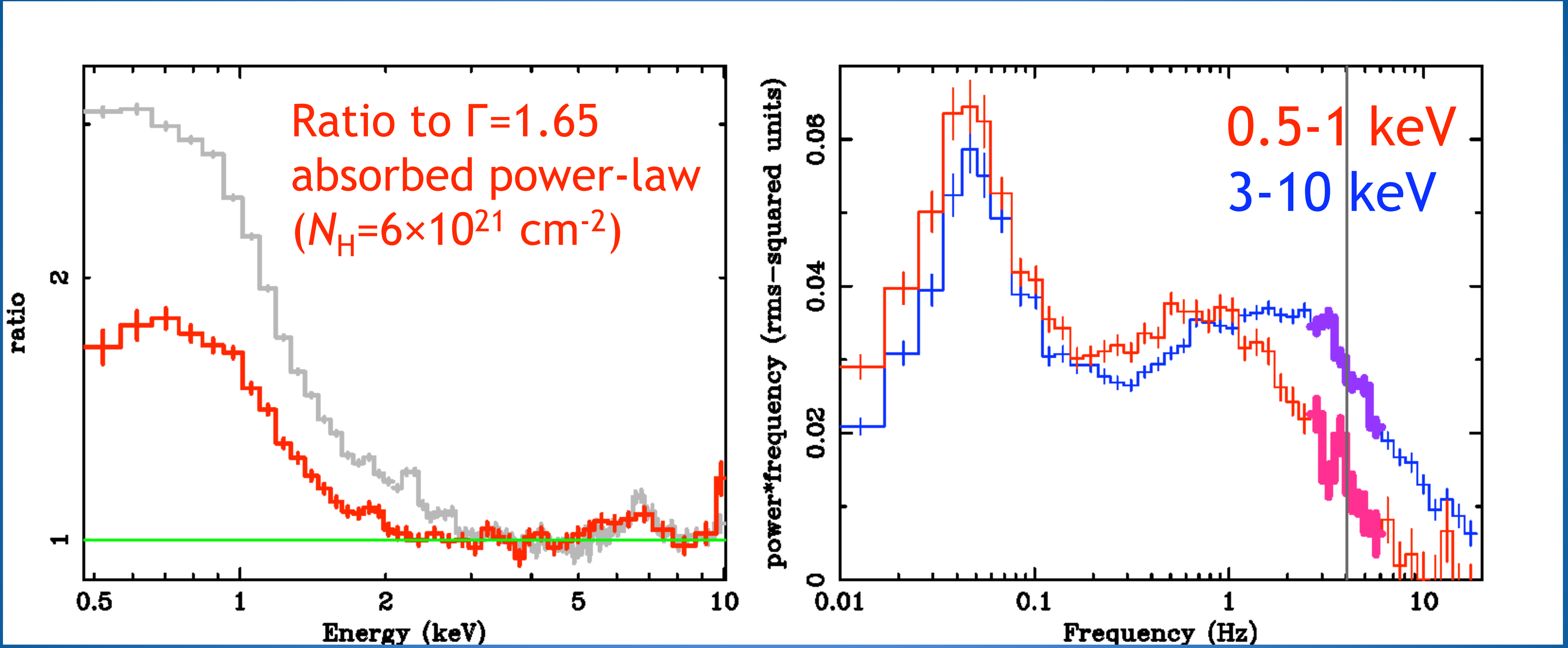
XMS 100 ksec, bright NLS1

Fe line is not accessible, but soft disklines clearly visible (note line cores with large lags)

Summary

- ✧ Timing measurements are a powerful probe of strong gravity which is independent of and complementary to spectral approaches
- ✧ For fast timing and lags, we find highest S/N in BHXRBs with high count rates
- ✧ Good measurements can also be obtained at soft energies for the brightest and most variable AGN

Fourier-resolved spectra



Fourier-resolved lag-energy spectra